Journal of Cleaner Production 170 (2018) 1594–1601

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Life cycle assessment of ammonia utilization in city transportation and power generation

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ARTICLE INFO

Article history:
Received 5 June 2017
Received in revised form
22 July 2017
Accepted 27 September 2017
Available online 28 September 2017

Handling Editor: Yutao Wang

Keywords:
Energy
Life cycle assessment
Ammonia
Power production
Transportation
Clean fuel

ABSTRACT

The main reason of climate change is particularly attributed to transportation and power generation in the world. Therefore, clean fuels alternatively emerge as potential solutions rather than carbon intensive hydrocarbons. In this study, carbon-free fuel ammonia is proposed to be utilized in the city transportation and power generation to reduce the environmental impacts of conventional fuels. Ammonia is electrochemically produced where required hydrogen is supplied from the wind-driven water electrolysis. The processes are analyzed from raw material extraction to vehicle disposal using life cycle assessment methodology. The results imply that greenhouse gas emissions from an ammonia driven vehicle are in the range of 100 g carbon dioxide eq. per km that is considerably lower than gasoline (270 g) and diesel (230 g) driven vehicles. Furthermore, using ammonia in the power plants can significantly reduce the total global warming potential corresponding to about 60% of natural gas-fired power plant.

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1. Introduction

Transportation is one of the main responsible sectors with a significant contribution to greenhouse gases (GHG) emissions and hence climate change. The majority of the CO_2 emissions in the world results from the combustion of fossil fuels. For example, in 2015, the energy sector of Canada containing stationary combustion, transportation, and fugitive resources released about 587 Mt of GHG that is almost 81% of entire GHG emissions in Canada (ECCC, 2017). The other releases were mostly produced by the agriculture sector with a value of 8% and industrial processes and product usage with a value of 7% where there was little influences caused by waste sector with a value of 3% (ECCC, 2017). Growths in releases since 2009 could be reasoned by upsurges in consumption of energy and fugitive emissions in oil and gas processes, upsurges in the quantity of heavyweight diesel vehicles in operation, higher depletion of halocarbons, and nonstop upsurges in the use of inorganic nitrogen fertilizers (ECCC, 2017). In 2015, the sector of agriculture was responsible for about 28% of CH_4 releases and 71% of N_2O releases in Canada. The key reasons of the emission tendency in the agriculture sector are the variations in livestock inhabitants and application of inorganic nitrogen fertilizers (ECCC, 2017). Ammonia is one of the main fertilizers in the world which is mainly produced by steam methane reforming method from natural gas.

Being a sustainable energy carrier that can be generated from any primary energy source, hydrogen can subsidize to a broadening of vehicle fuel resources and may offer the long term option of being generated from renewable resources.

Although diesel is normally fossil fuel-based, it can be produced from alternative materials such as soybean. In the LCA performed by Hu et al. (2008), it was shown that soybean-based diesel has 67% lower CO_2 emission than conventional diesel considering the whole cycle from source to wheel in the vehicle. Hydrogen fuel cell vehicles (FCV) are also one of the candidates of future transportation. As comparatively studied in Ahmadi and Kjeang (2017), when

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https://doi.org/10.1016/j.jclepro.2017.09.243
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conventional gasoline vehicles are switched to hydrogen fuel cell vehicles, considerable GHG reductions corresponding to about 72% can be achieved. Hydrogen fuel cells were also studied for buses in Australia to emphasize the importance of switching to clean fuels in transportation sector (Ally and Pryor, 2007). Sharma and Strezov (2017) performed a comprehensive study including the environmental and costing of the fuels in which they concluded that the environmental impacts of gasoline, biodiesel, ethanol and LPG dominate over the economic impacts, whereas, for compressed natural gas (CNG), hydrogen (FCV), and electricity (Battery electric vehicle: BEV), the economic impact dominates over the environmental impacts.

As an alternative energy carrier, transportation and power generation fuel; ammonia (NH_3), is another form of hydrogen fuel containing three atoms of hydrogen and one atom of nitrogen. Ammonia may also be burned directly in internal combustion engine (ICE) and generators with minor modifications. Compared to gasoline vehicles, ammonia-fueled vehicles do not produce direct CO_2 emission during operation. One of the key factors in decision of alternative fueled vehicles is to conduct life cycle assessment from cradle to grave. There have been various studies investigating the utilization of alternative fuels including ammonia in the transportation sector (Ashnani et al., 2015; Rose et al., 2013; Ahmadi and Kjeang, 2015; Baptista et al., 2013; Zhao and Tatari, 2015).

The combustion methods and characteristics of ammonia under various conditions have been extensively investigated in the literature (Ryu et al., 2014a, 2014b; Reiter and Kong, 2011; Zacharakis-Jutz and Kong, 2013; Haputhanthri et al., 2015). Reiter and Kong (2011) investigated the ammonia combustion with ammonia vapor which was introduced into the intake manifold and diesel fuel was injected into the cylinder to initiate combustion. The test engine they used was a four-cylinder, turbocharged diesel engine with slight modifications to the intake manifold for ammonia induction. The conventional diesel vehicles can be converted into ammonia vehicles by making some slight modifications such as addition of low pressure ammonia injectors and control system of injection. Moreover, the corrosive parts need to be replaced by the stainless steel to avoid any corrosion. The conversion system would be similar to currently used propane conversion kits. The injection timing is also important to note especially for dual fuel applications which was investigated by Tay et al. (2017a, 2017b) for ammonia/diesel/kerosene fuels. Ammonia was introduced into the engine via fumigation and pilot injection was used to ignite the premixed ammonia. In order to eliminate the difficulty of combusting ammonia, some researchers proposed the alternatives offered by using either diesel injection ignition plus port/direct injection of the ammonia, or jet ignition of a gasoline-like fuel (gasoline, methane, propone, hydrogen) plus port/direct injection of ammonia. A special NO_x catalyst would be required to reduce the emissions. The selective catalytic reductor can be adapted to combine ammonia with nitrogen to reduce the production of nitrogen oxides.

Note that there are multiple new pathways for ammonia synthesis options such as electrochemical routes. When hydrogen is produced from water electrolysis utilizing a renewable energy source such as wind or solar, environmentally pollutant emissions would noticeably diminish for ammonia production. Electrochemical synthesis of ammonia has been investigated intensively within the recent years (Xu et al., 2009; Murakami et al., 2002; Giddey et al., 2013; Kim et al., 2016; Wang et al., 2010; Garagounis et al., 2014; Kyriakou et al.,; Cui et al., 2016). In our recent studies, we have also conducted experiments for molten salt-based electrochemical ammonia synthesis (Bicer and Dincer, 2017a, 2017b). In addition, various life cycle assessment studies for ammonia production routes have been performed and reported where the source of hydrogen is varied from conventional to renewable resources (Bicer et al., 2016, 2017; Bicer and Dincer, 2017c,d).

Since solar and wind energy cannot be directly stored or continuously supplied in the form of electricity, it is required to convert solar and wind energy into a storable type of energy, preferably in the form of fuels. Ammonia is a significant candidate as a sustainable energy carrier for power generation of cities. Assisting electrochemical process with wind energy will lead an environmentally friendly method.

In this study, we present a life cycle assessment approach for ammonia utilization in city transportation and power production. The main objective of this study is to investigate the environmental impacts of using ammonia in passenger cars in cities and power generation in power plants instead of conventional fuels. The selected ammonia production method is wind energy-based electrochemical ammonia synthesis. Furthermore, the conventional gasoline and diesel driven vehicles and natural gas-fired power plants are also comparatively presented to emphasize the achieved total environmental impact reduction.

2. System description

The utilization of ammonia is mainly studied in two broad categories; transportation and power generation. The description of each system is separately given in this section.

2.1. City transportation

On average, lifetime performance of a passenger car is assumed to be 239,000 person km. Generally, the average utilization factor is expected to be 1.59–1.6 passengers per car. Henceforth, the lifetime of the selected vehicles is approximately 150,000 km. Here, the assessment comprises the following life cycle phases in which the functional unit is one km distance traveled:

- manufacturing of the vehicle,
- operation of the vehicle,
- maintenance of the vehicle, and
- disposal of the vehicle.

2.1.1. Passenger car manufacturing

The inventory contains processes of energy, water and material usage in passenger car manufacturing. Rail and road transport of materials is accounted for. The groundwork of plant is involved together with the issues such as land use, building, road and parking structure. The material consumption reflect a vehicle of Golf A4. The data for vehicle production are representative for manufacturing sites with an environmental management system.

The electricity in this step comes from a mixture of UCTE (Union for the Co-ordination of Transmission of Electricity) countries for all cases. The UCTE is the association of transmission system operators in continental Europe in which about 450 million people are supplied electricity. In the electricity usage process, electricity production in UCTE, the transmission network and direct SF6-emissions to air are included. Electricity losses during medium-voltage transmission and transformation from high-voltage are also accounted for. The conversion of high-medium voltage as well as the transmission of electricity at medium voltage are taken into account. Besides, the required high temperature is assumed to be from methane burned in industrial furnace higher than 100 kW which in turn contains fuel feed from high pressure gas network, infrastructure (boiler), emissions, and required electricity of operation. The considered vehicles here are all internal combustion

engine type passenger cars.

2.1.2. Maintenance

The inventory of maintenance of vehicles contains resources used for alternation parts and energy consumption of garages. Rail and road transportation of supplies is accounted for. The data are based on a LCI analysis of the Golf A4 (SimaPro, 2017; Ecoinvent, 2017). The required electricity comes from UCTE mix as explained in the previous paragraph.

2.1.3. Disposal of the vehicles

The inventory of vehicle disposal contains disposal processes for bulk materials. For the disposal of tires, a cut off allocation is applied. In addition, the transportation of tires to the cement works is taken into account. For the disposal of steel, aluminum, copper and tires, a cut off allocation is applied. Waste specific water together with air emissions from incineration and supplementary supply depletion for flue gas scrubbing are accounted for. Short term releases to river water and long term emissions to ground water from slag section and remaining material landfill are considered with process energy loads for municipal waste incineration plant (MSWI).

2.1.4. Production of fuel

The processes for fuel production is one of the main contributors in the whole life cycle. Here, ammonia is produced via electrochemical route for utilization in different systems. To compare the environmental impacts, crude oil and natural gas production processes are also explained. The transportation processes of the fuels from production site to the regional storage are accounted for the analysis.

2.1.4.1. Ammonia. In this study, H_2 is generated from wind energy-based electrolysis unit and directly used in the formation of electrochemical NH_3. Electrochemical synthesis of ammonia has previously tested and published in our previous work (Bicer and Dincer, 2017a,d). The required electricity for both electrochemical ammonia and wind electrolysis systems is supplied from wind turbines.

The first step includes only wind energy-based hydrogen production. In the second step, electrochemical ammonia synthesis process is modeled in SimaPro software where nitrogen gas comes from an air separation plant as shown in Fig. 1. Nitrogen production is the cryogenic air separation plant considering the plant construction, operation and maintenance where the inventory data are

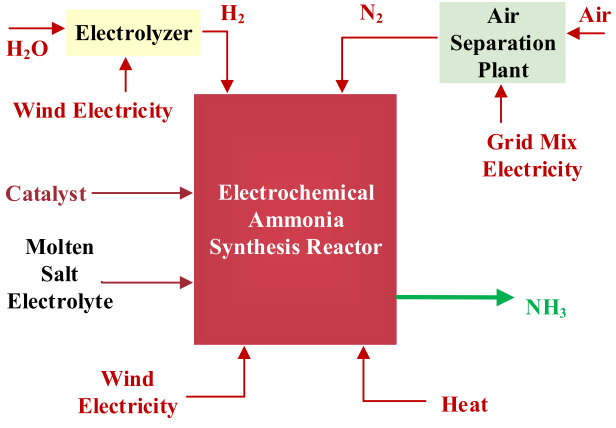

Fig. 1. The boundaries of the conducted LCA for electrochemical ammonia synthesis process.

taken from SimaPro database (SimaPro, 2017). Since it is a huge plant, the power is considered to be from U.S. grid mix.

The electricity and material inputs required for the life cycle assessment of electrochemical ammonia synthesis are derived from the experimental results previously given in the literature (Bicer and Dincer, 2017a, 2017d; Licht et al., 2014). The main energy and material requirements of this electrochemical ammonia synthesis are summarized in Table 1. Heat is not taken as input since it is supplied from any process as waste heat. The ammonia consumption rate of the vehicle is taken about 0.13 kg per person km which is calculated by using energy requirement of an internal combustion engine vehicle in GREET software (GREET, 2016).

2.1.4.2. Gasoline. All processes on the refinery site excluding the emissions from combustion facilities, including waste water treatment, process emissions and direct discharges to rivers are accounted for. The inventory data also includes the distribution of petroleum product to the final consumer including all necessary transports. Transportation of product from the refinery to the end user is considered together with operation of storage tanks and petrol stations. Emissions from evaporation and treatment of effluents are accounted for. Particulate emissions cover exhaust- and abrasions emissions. The gasoline consumption rate of the vehicle is taken as 0.065 kg per person km (GREET, 2016).

2.1.4.3. Diesel. Diesel is evaluated as low-sulfur at regional storage with an estimation for the total conversion of refinery production to low-sulfur diesel. An additional energy use (6% of energy use for diesel production in the refinery) has been estimated. The other processes are similar to gasoline. Particulate emissions cover exhaust- and abrasions emissions. The diesel consumption rate of the vehicle is taken as 0.055 kg per person km (GREET, 2016).

2.1.5. Operation of vehicles

The operation process of the vehicles is one of the key sections of life cycle analyses. In this phase, fuel consumption is involved. Direct airborne emissions of gaseous materials, particulate matters and heavy metals are accounted for. Particulate emissions cover exhaust- and abrasions emissions. Hydrocarbon emissions contain evaporation. Heavy metal emissions to soil and water produced by tire abrasion are accounted for. The values are based on operation of an average passenger car as mentioned before.

2.2. Power generation

In this section, a natural gas-fired power plant is taken as a base case and adapted for electricity production by combustion of ammonia. Wind-based ammonia which is produced in the preceding step is now used in the power plant to produce the required heat in the boiler. The description of the processes included in the LCA study are explained in the following section.

A gas power plant with a capacity of 100 MW is considered in the analysis. This step includes the most important materials used for construction. It includes also the energy requirements for construction. Transport is implicitly included in energy consumption. The life time for operation is assumed as 180,000 h. The average gas power plant is considered as 100 MWe. The data represent the average conditions for European plants (Rose et al., 2013). Same gas power plant is also used for power production via ammonia combustion.

After considering the gas power plant, electricity production from natural gas is evaluated. This step considers natural gas, burned in power plant, which in turn includes fuel input from high pressure network, infrastructure, emissions, and substances needed for operation. The module uses the average net efficiency of

Table 1
Main flows in electrochemical ammonia synthesis.

Parameter	Value	Unit
Ammonia (product)	1.875	mg
Hydrogen from Wind-based electrolysis	0.331	mg
Nitrogen, gas, at plant	1.543	mg
Wind electricity required for electrochemical ammonia synthesis	105	J
Transport, freight, rail, diesel	0.001125	kgkm
Transport, lorry, greater than 16 tonne	0.0001875	kgkm

natural gas power plants (Rose et al., 2013).

Ammonia is combusted in the gas power plant with a very similar approach to natural gas. Ammonia may have some difficulty to ignite compared with general fuels and slow burning velocity however, there have been specific studies (Iki et al., 2015; Valera-Medina et al., 2017; Nozari and Karabeyoğlu, 2015) related to ammonia combustion in gas turbines for power generation where the ignition control mechanism plays an important role. The main difference is the emissions caused during combustion where the inventory data are taken from the GREET software (GREET, 2016) and literature (Ryu et al., 2014a; Reiter and Kong, 2011; Nozari and Karabeyoğlu, 2015). Transportation of ammonia and natural gas to the power plant is included in the analysis.

3. Analysis methodology

In order to develop sustainable energy systems, multiple analyses are required implying comprehensive analyses including thermodynamics and environmental impact. The environmental impact, resource depletion, cost, and societal impact need to be taken into account as well as the efficiency and effectiveness. The technique of life-cycle assessment (LCA) is frequently used to examine the life cycle of a system from cradle to grave. Overall, when LCA is applied for energy systems, it determines an integrated efficiency of the complete process by considering final outputs over the lifespan and initial material inputs and the related energy and exergy flows. This type of cradle-to-grave analysis is particularly important for policy elaboration and decision making for sustainable development. LCA is one of the key tools for detecting the best paths leading to sustainable development.

There are numerous types of impact categories depending on the impact assessment method. Some of them are namely: depletion of abiotic sources, land use (competition, biodiversity loss, and life support function loss), climate change, human- and ecotoxicity, acidification, stratospheric ozone depletion, photo-oxidant formation, eutrophication, waste heat generation, noise and odor (in water and air), and ionizing radiation.

Some of the assumptions made for the present LCA analysis are listed as follows:

- The nitrogen is considered as gas from cryogenic air separation unit.
- The inputs used in calculations are feedstock, energy or electricity and emissions.
- The mass balance is used to identify the amount of hydrogen and nitrogen required for unit ammonia production.
- The functional unit for city transportation is 1 person km distance traveled whereas the functional unit for power generation is 1 MJ of electricity.

The LCA database ecoinvent (Ecoinvent, 2017) was used as source of background LCI data which is incorporated in SimaPro LCA software. Life cycle impact assessment, quantification of life-cycle environmental weights and potential impacts were carried out using the LCA software SimaPro 7.3.3 (SimaPro, 2017). The system boundaries for the city transportation and power generation are illustrated in Fig. 2. The production step of the fuels are previously mentioned in the preceding section.

CML 2001 method is a technique developed by a group of scientists under the lead of CML (Center of Environmental Science of Leiden University) counting a set of impact categories and characterization methods for the impact assessment step in 2001 (Simapro, 2017). CML 2001 method presents the results based on the environmental impact categories such as global warming, human toxicity and abiotic depletion. In this method, the results are mostly presented per equivalent substance amount such as kg CO_2 equivalent and kg SO_2 equivalent. The following environmental impact categories are considered for the assessment in this study:

- Abiotic Depletion Potential: Abiotic resources are natural resources including energy resources, such as natural gas and crude oil, which are considered as non-living. The unit is expressed as kg Sb. (antimony) eq.
- Acidification Potential: Acidification potential (AP) is related to acid deposition of acidifying contaminants on soil, groundwater, surface waters, biological organisms, ecosystems and substances. SO_2, NO_x and NH_x are the main acidifying contaminants. SO_2 equivalents/kg emission is considered to express the acidification. Most of the LCA impact assessment methods express acidification potential in terms of SO_2 equivalent. It is important to note that although the unit is expressed in SO_2 equivalents, the category includes the other acidifying substances including NO_x which can be one of the major concerns in ammonia combustion.

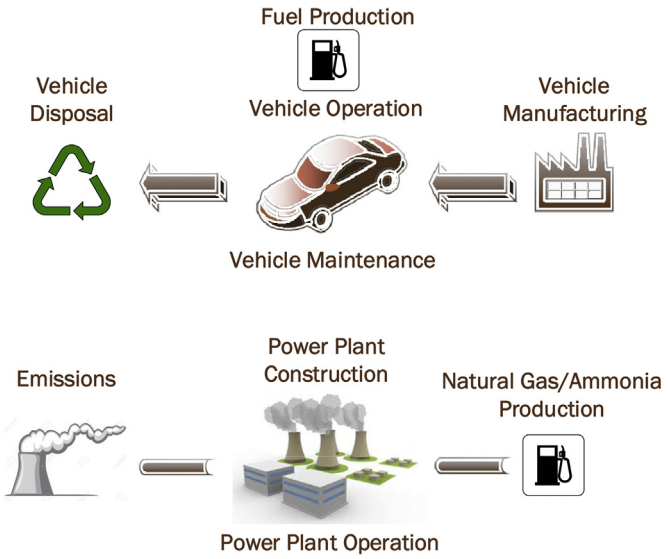

Fig. 2. The system boundaries for city transportation and power generation in the LCA study.

- Global Warming Potential: This category is related to greenhouse gas emissions and climate change. The unit kg CO_2 eq. is used to express the Global Warming Potential for time horizon 500 years (GWP500).
- Ozone Layer Depletion Potential: The thinning of the stratospheric ozone layer as a consequence of releases is described as stratospheric ozone depletion. The unit is given in kg CFC-11 eq.

4. Results and discussion

The LCA results are obtained using SimaPro 7.3 LCA software and categorized in two different sections namely; city transportation and power generation.

4.1. City transportation

The abiotic depletion potentials of the vehicles are comparatively illustrated in Fig. 3. The lowest potential is obtained from ammonia driven vehicle corresponding to about 0.00076 kg Sb eq per km. For gasoline driven vehicle, 89% of abiotic depletion is originated from operation of the vehicle whereas 8.6% is from manufacturing of the vehicle and 2% is from the maintenance of the vehicle. For diesel driven vehicle, operation process of the vehicle is responsible for about 87% of the complete abiotic depletion potential which is 2% lower than gasoline.

When reporting the contribution of different processes to overall impact category of the vehicles, 5% cut-off is applied. There are mainly four substances namely; hard coal (41%), nylon (8%), lignite (7%), natural gas (6%) being depleted in the entire life cycle of ammonia driven vehicle as shown in Fig. 4. The core reason of abiotic depletion is the process of ammonia fuel production where about 44.7% is caused by nitrogen production (which uses grid mix electricity) and 29% is caused by electricity production from wind (especially materials productions).

The acidification values of ammonia driven vehicle is higher than other fuels because of operation process. The source of acidification is predominantly the natural gas and hard coal at mine that is used for electricity production mix and eventually consumed in nitrogen production (about 33%). The acidification potentials of the vehicles are illustrated in Fig. 5. The ammonia, diesel and gasoline vehicles have acidification values of 0.0009, 0.00044 and 0.0007 kg SO_2 eq/km, respectively.

As shown in Fig. 6, the operation of ammonia vehicle represents almost 25% of the total acidification whereas 14% and 6% come from

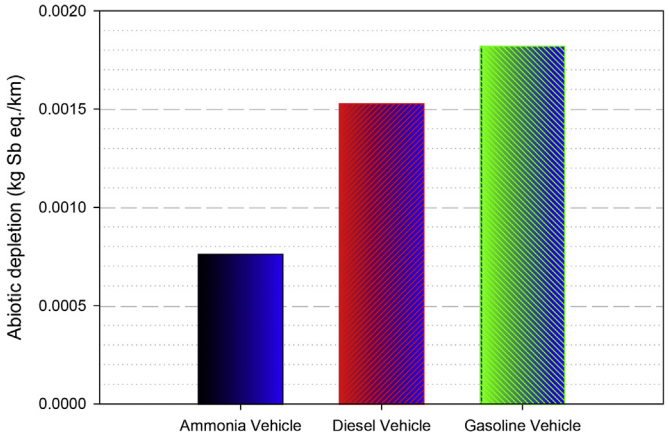

Fig. 3. Abiotic depletion potentials of gasoline, diesel and ammonia driven vehicles per traveled km.

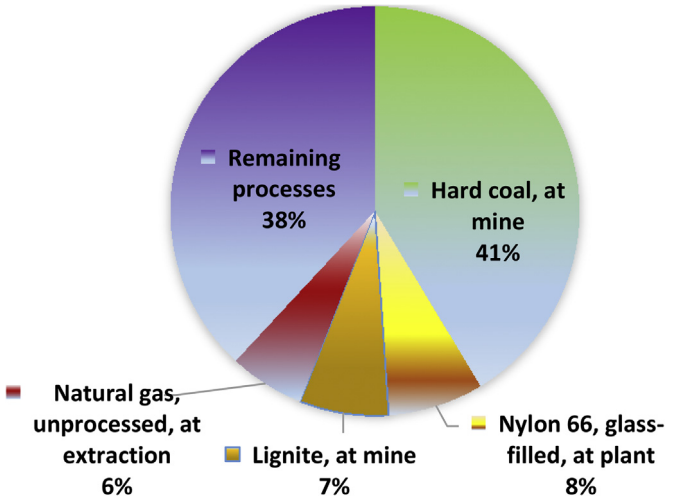
Remaining processes 38%
Hard coal, at mine 41%
Natural gas, unprocessed, at extraction 6%
Lignite, at mine 7%
Nylon 66, glass-filled, at plant 8%

Fig. 4. Contribution of various sub-processes to abiotic depletion potential of ammonia driven vehicle per km.

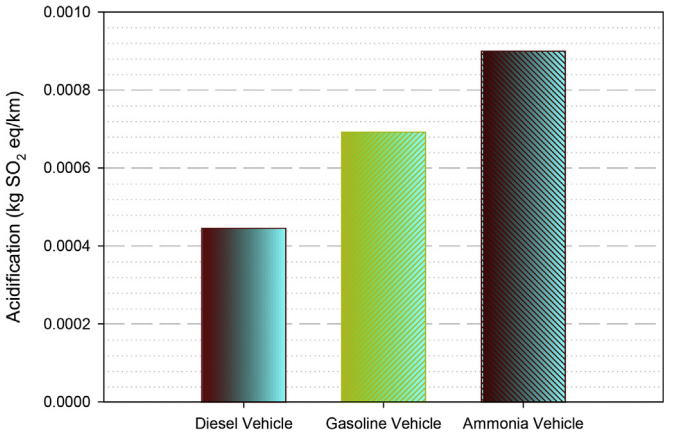

Fig. 5. Acidification potentials of gasoline, diesel and ammonia driven vehicles per traveled km.

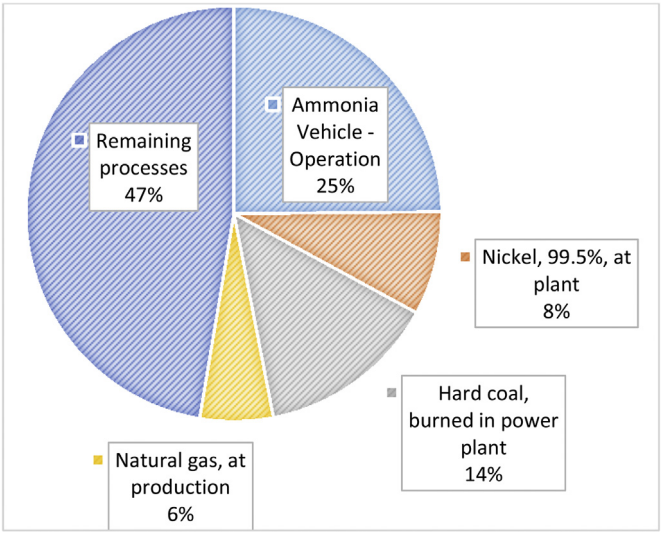
Remaining processes 47%
Ammonia Vehicle - Operation 25%
Nickel, 99.5%, at plant 8%
Hard coal, burned in power plant 14%
Natural gas, at production 6%

Fig. 6. Contribution of various sub-processes to acidification potential of ammonia driven vehicle per km.

hard coal and natural gas, respectively which are used in electricity requirement of the processes. Ammonia production reactor contributes about 7.8% of acidification value.

The total greenhouse gas (GHG) emissions from the vehicles are shown in Fig. 7. As a carbon-free fuel, ammonia, has quite low GHG emissions in the complete life cycle corresponding to about 0.1 kg CO_2 eq per km. On the other hand, gasoline vehicle emits about 0.27 kg CO_2 eq/km. Note that these values represent the complete life cycle including the vehicle manufacturing, maintenance and disposal. In addition, the ammonia is sourced from wind electrolysis process which is a clean and environmentally friendly option.

About 76% of GHG emissions is caused by operation of gasoline vehicle as shown in Fig. 8. Furthermore, the refinery gas and heavy fuel oil burned in the furnaces contribute about 5% and 3%, respectively.

In terms of stratospheric ozone layer depletion, diesel vehicle has the highest impact on environment as shown in Fig. 9. The depletion of ozone layer is one of the main reasons of climate change which is actually caused by carbon emissions to the atmosphere. Since diesel and gasoline have huge amount of carbon substance, they have higher ozone layer depletion values.

The highest is equal to 3×10^{-8} kg CFC-11 eq. per km for diesel vehicle. The lowest contribution is from ammonia corresponding to 4.12×10^{-9} kg CFC-11 eq/km. Because there is no direct CO_2 emission during operation of ammonia driven vehicles.

4.2. Power generation

Ammonia can be combusted for power generation similar to natural gas and propane. In this case, the emission during combustion is considerably lower than natural gas as compared in Table 2 for various impact categories.

The global warming potential of 1 MJ electricity production is about 0.08 kg CO_2 eq. and 0.13 kg CO_2 eq. for ammonia and natural gas-fired power plants, respectively. 93% of GHG emissions are originated from wind electrolysis-based electrochemical ammonia production phase during entire life cycle for electricity production from ammonia. About 42% is emitted from nitrogen production, 27% is from electricity production in wind power plant, and 16.5% is from hydrogen production via wind electrolysis. About 5.9% of GHG emissions from ammonia-fired power plant is because of dinitrogen monoxide and 4% is because of carbon monoxide. As shown in Fig. 10, only 6% of global warming potential is reasoned by ammonia combustion in the plant. On contrast for natural gas-fired power plant, about 97% of GHG emissions are caused by natural has burned in the power plant. 98.6% of these emissions are carbon dioxide.

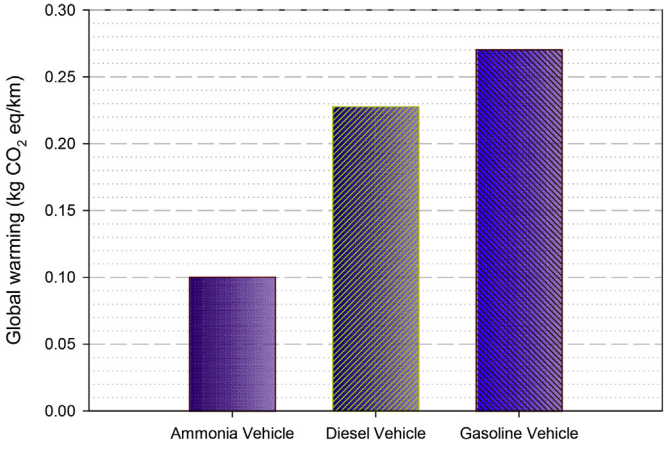

Fig. 7. Global warming potentials of gasoline, diesel and ammonia driven vehicles per traveled km.

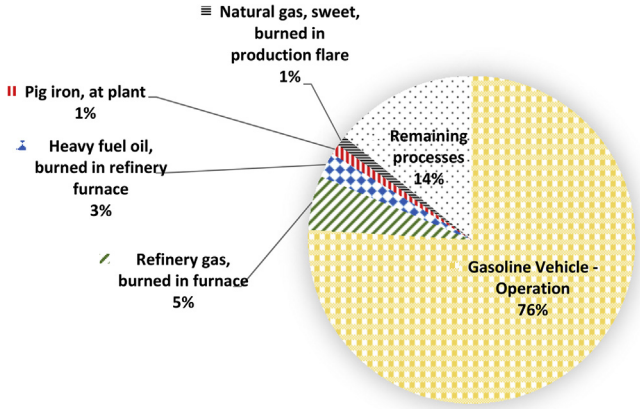
Natural gas, sweet, burned in production flare 1%
Pig iron, at plant 1%
Heavy fuel oil, burned in refinery furnace 3%
Refinery gas, burned in furnace 5%
Remaining processes 14%
Gasoline Vehicle - Operation 76%

Fig. 8. Contribution of various sub-processes to global warming potential of gasoline driven vehicle per km.

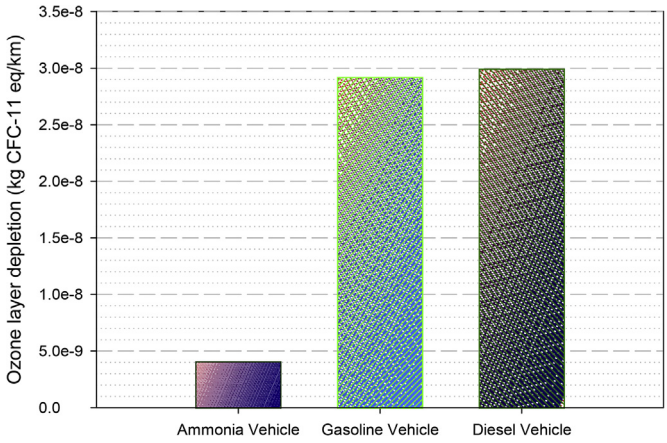

Fig. 9. Ozone layer depletion potentials of gasoline, diesel and ammonia driven vehicles per traveled km.

Similarly, ozone layer depletion of ammonia-based electricity production is almost half of natural gas. Because, almost 90% of ozone layer depletion is caused by long distance natural gas transport through pipelines whereas 4% is caused by natural gas production for electricity production via natural gas. On the other hand, transport of natural gas decreases to 21.5% for ammonia-fired power plant. However, the production of crude oil is the primary contributor to depletion of ozone layer in this case. This is mainly caused by transport of ammonia to the power plant via railway and trucks which uses diesel fuel.

In terms of acidification potential, the combustion of ammonia has a huge share corresponding to about 81% as shown in Fig. 11. It is the only impact category in which ammonia yields greater environmental effect. This is mainly because of possible ammonia leaks to the environment. The release of ammonia has a share of 73% whereas sulfur dioxide and nitrogen oxides have shares of 9.9% and 8.7%, respectively. On the other hand, in natural gas-fired power plant, nitrogen oxides have a share of 89% and sulfur dioxides have a share of 8%. These are basically originated from natural gas combustion.

The abiotic depletion potential of electricity production from natural gas-fired power plant is obviously because of natural gas and ammonia consumption in the plant. Ammonia reactor is

Table 2
The comparison of electricity production from ammonia and natural gas for different environmental impact categories.

Impact category	Unit	Electricity from ammonia-fired power plant	Electricity from natural gas-fired power plant
Abiotic depletion	kg Sb eq/MJ	0.000591,658	0.001127084
Acidification	kg SO_2 eq/MJ	0.002930042	7.2×10^{-5}
Global warming 500a	kg CO_2 eq/MJ	0.082909515	0.1330023
Ozone layer depletion 40a	kg CFC-11 eq/MJ	2.74×10^{-9}	5.92×10^{-9}

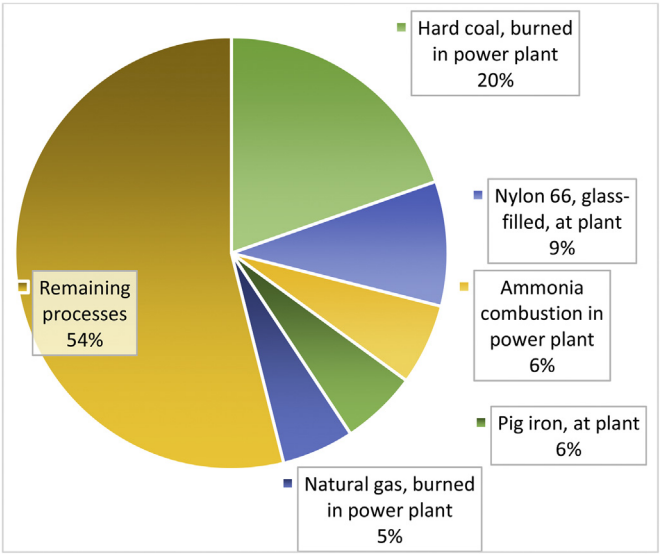
Hard coal, burned in power plant 20%
Nylon 66, glass-filled, at plant 9%
Ammonia combustion in power plant 6%
Pig iron, at plant 6%
Natural gas, burned in power plant 5%
Remaining processes 54%

Fig. 10. Contribution of various sub-processes to global warming potential of 1 MJ energy generation in ammonia-fired power plant (5% cut-off).

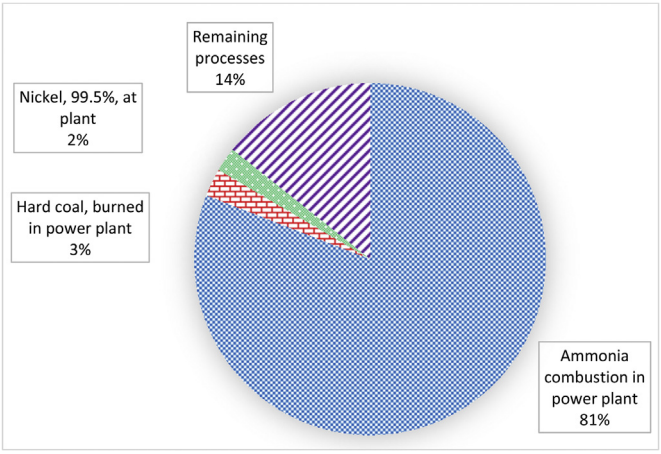

Fig. 11. Contribution of various sub-processes to acidification potential of 1 MJ energy generation in ammonia-fired power plant (2% cut-off).

responsible about 2% of total abiotic depletion whereas transport of ammonia to the plant has a share of about 6.6%. Hard coal is the main depleting substance (with a share of 55%) for ammonia-based electricity production, followed by natural gas (23%) and crude oil (16%), respectively.

5. Conclusions

The reduction of greenhouse gases and other environmental impacts are possible by using carbon-free fuels such as ammonia in city transportation and power production. This study shows the advantages of using ammonia in passenger cars and power plants by comparatively evaluating the environmental impacts; acidification, abiotic depletion, ozone layer depletion and global warming potential. Fuel ammonia is produced from wind energy-based water electrolysis in an electrochemical reactor using molten salt electrolyte. As an abundant and clean renewable energy source, wind, can be used in clean ammonia synthesis applications which can considerably reduce the total environmental impact. The electrochemical ammonia synthesis brings the flexibility of utilizing renewable electricity that is an alternative to conventional energy intensive centralized ammonia production plants. The results show that ammonia driven vehicle can diminish the greenhouse gas emissions down to 100 g per km compared to gasoline vehicle having a value of 270 g per km. This implies significant reduction in GHG emission for cities. Similarly, for 1 MJ electricity generation, ammonia-fired power plant emits about 0.083 kg CO_2 eq. whereas natural gas-fired power plant releases about 0.13 kg CO_2 eq. About 97% of global warming potential of natural gas-based electricity production occurs during combustion in the plant, however the main source of GHG emissions for ammonia-based electricity production is the production process of ammonia (93%). It is shown that replacing conventional fuels with carbon-free ammonia, the intensive effect of city transportation and power generation can be considerably mitigated.

Acknowledgement

The authors acknowledge the support provided by the Natural Sciences and Engineering Research Council of Canada.

Nomenclature

AP	Acidification potential
BEV	Battery electric vehicle
CML	Center of Environmental Science of Leiden University
FCV	Fuel cell vehicle
GHG	Greenhouse gas
GWP	Global warming potential
ICE	Internal combustion engine
LCA	Life cycle assessment
LCI	Life cycle inventory
LHV	Lower heating value
MSWI	Municipal waste incineration plant
UCTE	Union for the Co-ordination of Transmission of Electricity

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